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The implementation of network-centric warfare technologies is an abiding, critical interest of Air Force Science and Technology efforts for the Warfighter. Wireless communications, strategic signaling are areas of critical Air Force Mission need. Autonomous networks of multiple, heterogeneous Throughput enhancement and robust connectivity in communications and sensor networks are critical factors in net-centric USAF operations. This research directly supports the Air Force vision of information dominance and the development of "anywhere, anytime" operational readiness.

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| **Institution:** | YALE UNIVERSITY |
| **Primary Investigator:** | Dr. Edmund Yeh |
| **Invention Ind:** | none |
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| **Program Manager:** | Bob Bonneau |

## Objective:

Expand and extend the state-of-the-art in the control of wireless communications networks possessing stochastic message arrival and transmission patterns.

## Approach:

Investigation will proceed along the lines of network traffic models. A flow model can be employed which is relevant for situations where arrival statistics and channel characteristics vary slowly. In this case minimum delay can be achieved through distributed control algorithms that jointly optimize power control, routing, and congestion factors. A second stochastic model approach updates the network queue state, node-transmission powers amongst others, allowing for power control, scheduling, and routing algorithms to maximize network throughput under time-varying conditions of random traffic.

## Progress:

**Year:** 2008      **Month:** 01

Annual Report for AFOSR FA9550-06-1-0135 "Theory, Design, and Algorithms for Optimal Control of Wireless Networks"

Edmund Yeh
Yale University

The main focus of this project is the development of fundamental theory, designs, and algorithms for the optimal control of mobile wireless networks. Over the past year, we have concentrated on the following research activities:

1. Analysis of flow models for the optimization of wireless networks. Design of distributed algorthms which jointly optimize network functionalities such as power control, rate allocation, routing, and congestion control for ad hoc wireless networks.

2. Development of distributed algorithms which find the optimal coding subgraphs for wireless networks employing network coding.

3. Analysis of stochastic models for wireless networks where random packet arrivals and queuing are explicitly modelled. Development of throughput optimal distributed power control and rate allocation algorithms which adaptively stabilizes wireless networks with random arrivals and queuing.

4. Distributed optimization of wireless networks satisfying duplexing constraints, where nodes cannot transmit and receive

## Progress:

**Year:** 2008     **Month:** 01

at the same time on the same frequency band. Analysis and design of distributed spectrum allocation algorithms which yield a feasible frequency allocation satisfying the duplexing constraints. Development of frequency-selective power control, routing, and congestion control scheme for a given feasible frequency allocation.

5. Simulation of distributed algorithms accomplishing the goals listed in 1-4.

Detailed results for the above research activities:

1. We have established a unified, coherent framework in which disparate network functionalities such as power control, rate allocation, routing, and congestion control can be jointly optimized for wireless networks. In this framework, power control, routing, and congestion control variables are chosen to minimize convex link costs reflecting, for instance, average packet delay in the wireless network. We have characterized the conditions under which the total network cost (sum of link costs) is minimized. For interference-limited wireless networks under a signal-to-interference-and-noise model, we have also developed a set of distributed power control, routing, and congestion control algorithms which iteratively adjust control variables so as to minimize the total network cost, using limited communication overhead. These algorithms are guaranteed to converge from any initial point with finite cost. For networks with more general coding and modulation schemes where the achievable rate region is convex, we have characterized the conditions for optimal operation. To our knowledge, the distributed algorithms developed here are the first which provably jointly optimize disparate network functionalities in one framework.

2. In wireless networks involving network coding, information is not simply routed, but jointly coded to increase network throughput. In these new networks, one question is how to design network codes jointly with physical layer parameters to minimize total network cost. We have developed a set distributed power control, rate allocation, and congestion control algorithms which yield the minimum-cost network coding configuration in a multicast wireless network. These algorithms are an extension of the algorithms for the non-coded networks. In order to arrive at these results, we show that the routing methodology can be adapted to the network-coded context, where now the routed flows are not the actual link flows, but the information flows being combined on the links.

3. We have analyzed stochastic models of wireless networks where random packet arrivals and queuing are explicitly modelled. For these networks, it is known that the Tassiulas-Ephremides Backpressure Algorithm is throughput optimal. That is, the algorithm adaptively stabilizes the network whenever the arrival rates are in the network stability region.

**Year:** 2008     **Month:** 05

We have studied the problem of large-scale wireless network resilience to node failures from a percolation-based perspective. In practical wireless networks, it is often the case that nodes with larger degrees (i.e. more neighbors) are more likely to fail, due to enemy attack, energy depletion, or natural hazards. We modeled this phenomenon as a degree-dependent site percolation process on random geometric graphs. In particular, we obtained analytical conditions for the existence of phase transitions within this model. Furthermore, in energy-constrained wireless and sensor networks carrying data traffic, the failure of one node results in redistribution of the load onto other nearby nodes, which now need to expend more energy to carry the extra traffic. If these nodes fail due to energy depletion, then this process can result in cascading failure. We analyzed this cascading failures problem in large-scale wireless networks, and showed that it is equivalent to a degree-dependent site percolation on random geometric graphs. We obtained analytical conditions for cascades in this model.

**Year:** 2009     **Month:** 06     **Final**

1. Analysis of flow models for the optimization of wireless networks. Design of distributed algorithms which jointly optimize network functionalities such as power control, rate allocation, routing, and congestion control for ad hoc wireless networks.

2. Development of distributed algorithms which find the optimal coding subgraphs for wireless networks employing

## Progress:

**Year:** 2009    **Month:** 06    **Final**

network coding.

3. Analysis of stochastic models for wireless networks where random packet arrivals and queuing are explicitly modelled. Development of throughput optimal distributed power control and rate allocation algorithms which adaptively stabilizes wireless networks with random arrivals and queuing.

4. Distributed optimization of wireless networks satisfying duplexing constraints, where nodes cannot transmit and receive at the same time on the same frequency band. Analysis and design of distributed spectrum allocation algorithms which yield feasible a frequency allocation satisfying the duplexing constraints. Development of frequency-selective power control, routing, and congestion control scheme for a given feasible frequency allocation.

5. Throughput optimal control of stochastic wireless networks with random packet arrivals and cooperative communication capabilities, where nodes combine to form virtual antenna arrays.

6. Simulation of distributed algorithms accomplishing the goals listed in 1-5.

AFOSR Final Performance and Patent Report

**Project Title:** Theory, Design, and Algorithms for Optimal Control of

Wireless Networks

**Award Number:** FA9550-06-1-0135

**Start Date:** March 1, 2006

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#### Accomplishments/New Findings:

The main focus of this project is the development of fundamental theory, designs, and algorithms for the optimal control of mobile wireless networks. Over the duration of the reporting period, we have concentrated on the following research activities:

1. Analysis of flow models for the optimization of wireless networks. Design of distributed algorithms which jointly optimize network functionalities such as power control, rate allocation, routing, and congestion control for ad hoc wireless networks.

2. Development of distributed algorithms which find the optimal coding subgraphs for wireless networks employing network coding.

3. Analysis of stochastic models for wireless networks where random packet arrivals and queuing are explicitly modelled. Development of throughput optimal distributed power control and rate allocation algorithms which adaptively stabilizes wireless networks with random arrivals and queuing.

4. Distributed optimization of wireless networks satisfying duplexing constraints, where nodes cannot transmit and receive at the same time on the same frequency band. Analysis and design of distributed spectrum allocation algorithms which yield a feasible frequency allocation satisfying the duplexing constraints. Development of frequency-selective power control, routing, and congestion control scheme for a given feasible frequency allocation.

5. Throughput optimal control of stochastic wireless networks with random packet arrivals and cooperative communication capabilities, where nodes combine to form distributed antenna arrays.

6. Simulation of distributed algorithms accomplishing the goals listed in 1-5.

#### Summary:

The following are detailed results for the above research activities:

1. We have established a unified, coherent framework in which disparate network functionalities such as power control, rate allocation, routing, and congestion control can be jointly optimized for wireless networks. In this framework, power control, routing, and congestion control variables are chosen to minimize convex link costs reflecting, for instance, average packet delay in the wireless network. We have characterized the conditions under which the total network cost (sum of link costs) is minimized. For interference-limited wireless networks under a signal-to-interference-and-noise model, we have also developed a set of distributed power control, routing, and congestion control algorithms which iteratively adjust control variables so as to minimize the total network cost, using limited communication overhead. These algorithms are

guaranteed to converge from any initial point with finite cost. For networks with more general coding and modulation schemes where the achievable rate region is convex, we have characterized the conditions for optimal operation. To our knowledge, the distributed algorithms developed here are the first which provably jointly optimize disparate network functionalities in one framework.

2. In wireless networks involving network coding, information is not simply routed, but jointly coded to increase network throughput. In these new networks, one question is how to design network codes jointly with physical layer parameters to minimize total network cost. We have developed a set distributed power control, rate allocation, and congestion control algorithms which yield the minimum-cost network coding configuration in a multicast wireless network. These algorithms are an extension of the algorithms for the non-coded networks. In order to arrive at these results, we show that the routing methodology can be adapted to the network-coded context, where now the routed flows are not the actual link flows, but the information flows being combined on the links.

3. We have analyzed stochastic models of wireless networks where random packet arrivals and queuing are explicitly modelled. For these networks, it is known that the Tassiulas-Ephremides Backpressure Algorithm is throughput optimal. That is, the algorithm adaptively stabilizes the network whenever the arrival rates are in the network stability region. In wireless networks with mutually interfering links, however, the implementation of the Backpressure Algorithm is typically not distributed. Within the context of CDMA-based multi-hop networks, we have developed a set of power control and rate allocation algorithms which implements the backpressure algorithm in a distribue manner with low communication overhead. As these algorithms require time to converge to a neighborhood of the optimum, the optimal rates determined by the Backpressure Algorithm can only be found iteratively over time. For this, we have shown that an iterative version of the Backpressure Algorithm with convergence time remains throughput optimal. To our knowledge, this is one of the first results which achieve distributed throughput optimal control of stochastic wireless networks.

4. In wireless networks, nodes typically must satisfy the constraint that a single transceiver cannot simultaneously send and receive at the same time over the same frequency band. This constraint, called the duplexing constraint, is less restrictive but more fundamental than primary and secondary conflict constraints often analyzed in the scheduling literature. In order to resolve the duplexing conflict in wireless networks, we have developed a new spectrum allocation scheme where the given spectrum is divided into multiple subbands and conflict-free links on each subband are activated. We have found that the minimum number of subbands needed to yield a feasible spectrum allocation grows asymptotically at a logarithmic rate with the chromatic number of the network connectivity graph. We have designed a simple distributed and asynchronous algorithm which constructs a feasible spectrum allocation given enough subbands. Finally, we have incorporated the distributed spectrum allocation scheme into a set of distributed optimization algorithms for wireless networks satisfying the duplexing constraints. In this setting, a feasible spectrum allocation/link activation is first found using the distributed algorithms developed here, and then jointly optimal power control, rate allocation, routing, and congestion control are performed on a frequency selective basis to minimize total network cost.

5. In cooperative relaying, packets are not forwarded by traditional hop-by-hop transmissions between pairs of nodes. Instead, several nodes cooperate with each other to forward a packet by, for example, forming a distributed antenna array. To date, such schemes have been primarily investigated at the physical layer with the focus on communication of a single end-to-end flow. In this project, we consider cooperative relay networks with multiple stochastically varying end-to-end flows. The traffic from each flow is queued within the network until it can be forwarded. For such networks, we study network control policies that take into account queue dynamics to jointly optimize routing, scheduling and allocation. Specifically, we have developed a throughput optimal policy, i.e., a policy that stabilizes the network for any arrival rate in its stability region. This policy is a generalization of the well-known backpressure algorithm, which takes into account the cooperative gains in the network.

6. In order to assess the practical relevance of the algorithms we designed in 1-5, we have performed extensive simulations where the algorithms are applied to wireless networks with various topologies and parameters. In particular, we have shown that the distributed power control, rate allocation, and routing algorithms significantly outperform existing protocols (such as AODV) in terms of total network cost. Furthermore, we have shown that even when components of our algorithms (such as power control) are run jointly with existing algorithms, significant gains result. This points to the great potential for the practical implementation of these algorithms.

**Personnel:**

Faculty: Edmund M. Yeh (Yale)

Graduate Students: Jian Cao (Yale)

    Yufang Xi (Yale); M.Phil. degree in EE, May 2006

    Zhenning Kong (Yale); M.Phil. degree in EE, May 2007

**Publications/Accepted or In Print** (partially or fully supported by this project, 2005-present):

1. Yufang Xi and Edmund M. Yeh. "Node-Based Optimal Distributed Power Control, Routing, and Congestion Control in Wireless Networks." *IEEE Transactions on Information Theory*, Vol. 54, No. 9, September 2008, pp. 4081-4106.

2. Jian Cao and Edmund M. Yeh, "Power-Delay Tradeoff Analysis for Communication over Fading Channels with Feedback." *Proceedings of the International Symposium on Information Theory*, Toronto, Canada, July 6-11, 2008.

3. Yufang Xi and Edmund M. Yeh, "Spectrum Allocation, Power Control, Routing, and Congestion for Wireless Networks with Duplexing Constraints." *Proceedings of the Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, CA, November 4 - 7, 2007.

4. Edmund M. Yeh and Randall A. Berry, "Throughput Optimal Control of Cooperative Relay Networks." *IEEE Transactions on Information Theory: Special Issue on Models, Theory, and Codes for Relaying and Cooperation in Communication Networks*, Vol. 53, No. 10, October 2007, pp. 3827-3833.

5. Yufang Xi and Edmund M. Yeh, "Distributed Algorithms for Spectrum Allocation, Power Control, Routing, and Congestion Control in Wireless Networks." *Proceedings of the Eighth ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc)*, Montreal, Canada, September 9 - 14, 2007.

6. Edmund M. Yeh and Randall A. Berry, "Throughput Optimal Control of Wireless Networks with Two-hop Cooperative Relaying." *Proceedings of the 2007 International Symposium on Information Theory*, Nice, France, June 24 - 29, 2007.

7. Yufang Xi and Edmund M. Yeh, "Spectrum Allocation in Wireless Networks with Duplexing Constraints." *Proceedings of the 2007 International Symposium on Information Theory*, Nice, France, June 24 - 29, 2007.

8. Jian Cao and Edmund M. Yeh, "Asymptotically Optimal Multiple-access Communication via Distributed Rate Splitting." *IEEE Transactions on Information Theory*, Vol. 53, No. 1, January 2007, pp. 304-319.

9. Yufang Xi and Edmund M. Yeh, "Distributed Algorithms for Maximum Throughput in Wireless Networks." *Proceedings of the Fourteenth European Signal Processing Conference*, Florence Italy, September 4 - 8, 2006.

10. Yufang Xi and Edmund M. Yeh, "Optimal Distributed Power Control and Routing in Wireless Networks." *Proceedings of the 2006 International Symposium on Information Theory*, Seattle, WA, July 9 - 14, 2006.

11. Yufang Xi and Edmund M. Yeh, "Optimal Capacity Allocation, Routing, and Congestion Control in Wireless Networks," *Proceedings of the 2006 International Symposium on Information Theory*, Seattle, WA, July 9 - 14, 2006.

12. Yufang Xi and Edmund M. Yeh, "Distributed Algorithms for Minimum Cost Multicast with Network Coding in Wireless Networks," *Proceedings of the Second Workshop on Network Coding, Theory, and Applications*, Boston, MA, April 7, 2006.

13. Yufang Xi and Edmund M. Yeh, "Throughput Optimal Distributed Control of Stochastic Wireless Networks," *Proceedings of the Fourth International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt'06)*, Boston, MA, April 3-7, 2006.

14. Yufang Xi and Edmund M. Yeh, "Node-based Optimal Distributed Power Control, Routing, and Congestion Control in Wireless Networks," *Proceedings of the Conference on Information Sciences and Systems*, Princeton, NJ, March 22 - 24, 2006.

**Interactions/Transitions** (partially or fully supported by this project, 2005-2007):

Other interactions include the following technical presentations:

1. **"Distributed Algorithms for Optimal Control of Wireless Networks**." Department of Information Engineering, Chinese University of Hong Kong, Hong Kong, China, October 4, 2007.

2. "Distributed Algorithms for Optimal Control of Wireless Networks," Mathematical Research Center, Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey, August 7, 2007.

3. "Distributed Algorithms for Optimal Control of Wireless Networks," *Summer Research Institute*, Information Theory Laboratory, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland, July 11, 2007.

4. "Distributed Algorithms for Optimal Control of Wireless Networks," Heinrich Hertz Institute and Technical University of Berlin, Berlin, Germany, July 4, 2007.

5. "Distributed Algorithms for Optimal Control of Wireless Networks," Wireless Networking and Communications Seminar, Department of Electrical and Computer Engineering, University of Texas at Austin, April 6, 2007.

6. "Distributed Algorithms for Optimal Control of Wireless Networks," Networking, Communications, and DSP Seminar, Department of Electrical Engineering and Computer Sciences, University of California at Berkeley, February 26, 2007.

7. "Distributed Optimization Algorithms for Network Coding," INFORMS Annual Meeting, Pittsburgh, PA, November 6, 2006.

8. "Distributed Algorithms for Optimal Control of Wireless Networks," Information Systems Laboratory Seminar, Department of Electrical Engineering, Stanford University, November 2, 2006.

9. "Distributed Algorithms for Optimal Control of Wireless Networks," Coordinated Sciences Laboratory Communications Group Seminar, University of Illinois at Urbana-Champaign, IL, May 1, 2006.

10. "Throughput Optimal Control of Cooperative Relay Networks," Workshop on the Mathematics of Relaying and Cooperation in Communication Networks, Mathematical Sciences Research Institute, Berkeley, CA, April 10 - 12, 2006.

**New Discoveries, Inventions, or Patent Disclosures** (2006-2008):

None

**Honors/Awards** (2006-2008):

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